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Research article

Research alignment in the U.S. national park system: Impact of transformative science policy on the supply and demand for scientific knowledge for protected area management

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ABSTRACT

The US National Park System encompasses diverse environmental and tourism management regimes, together governed by the 1916 Organic Act and its dual mandate of conservation and provision of public enjoyment. However, with the introduction of transformative science policy in the 2000's, the mission scope has since expanded to promote overarching science-based objectives. Yet despite this paradigm shift instituting "*science for parks, parks for science*", there is scant research exploring the impact of the National Park Science Policy on the provision of knowledge. We address this gap by developing a spatiotemporal framework for evaluating research alignment, here operationalized via quantifiable measures of supply and demand for scientific knowledge. Specifically, we apply a machine learning algorithm (Latent Dirichlet analysis) to a comprehensive park-specific text corpus (combining official needs statements -i.e. demand- and scientific research metadata -i.e. supply-) to define a joint topic space, which thereby facilitates quantifying the direction and degree of alignment at multiple levels. Results indicate an overall robust degree of research alignment, with misaligned topics tending to be over-researched (as opposed to over-demanded), which may be favorable to many parks, but is inefficient from the park system perspective. Results further indicate that the transformative science policy exacerbated the misalignment in mandated research domains. In light of these results, we argue for improved decision support mechanisms to achieve more timely alignment of research efforts towards distinctive park needs, thereby fostering convergent knowledge co-production and leveraging the full value of National Parks as living laboratories.

1. Introduction

Scientific knowledge constitutes an important input for management of socio-environmental systems, where a deep understanding of their complex processes, inter-dependencies, and systemic risk are crucial (Amaral and Uzzi, 2007), (Helbing, 2013), (McNie, 2007). The demand for such knowledge often derives from distinct sectors (society, academia, industry, non-profit organizations, government), and so the supply of knowledge may be inadequate to address the overarching social, environmental, and/or technological challenges (McNie, 2007), (Arroyave et al., 2021), (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Devereux and Cook, 2000), (Petersen et al., 2021), (Rafols and Yegros, 2017), (Scown et al., 2019), (Soukup, 2007), (Tambe et al., 2023).

Recent efforts to evaluate research in various problem domains such as public health, food security and nutrition, and climate science (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Sarewitz and Pielke, 2007) illustrate the mismatch between the supply and demand for scientific knowledge (i.e., research misalignment), and bring relevant information to science policy and evaluation. However, despite the importance of configuring efficient streams of knowledge production for timely and

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prioritized action, little is known regarding different factors and drivers that might affect the degree of research alignment, including science policy and policy change. Against this backdrop, this work develops a framework for evaluating research alignment and uses as case study the protected areas dominated as 'national parks' that are part of the U.S. National Park System– designated public areas belonging to the International Union for Conservation of Nature (IUCN) Category II protected areas, featuring very high levels of protection and regulation. Given the diversity of protected areas encompassed by the U.S. National Park System (e.g. Battlefields, Monuments) and their managerial regimes, we limited our study to 'national parks' as the largest and the most emblematic protected areas in the system.

The U.S. National Parks (hereafter referred to as *parks* for brevity) are representative pieces of both natural and cultural heritage, thereby embodying potential to deliver insights about global change to both scientists and society at large, in particular, by establishing counterfactual baselines corresponding to low levels of anthropogenic influence (Dilsaver, 2009), (Fancy and Bennetts), (Rodhouse et al., 2016). Parks and the scientific community have been involved in a mutually beneficial relationship since the first established park in 1872 (Yellowstone National Park), as parks are exceptional living laboratories that facilitate the large-scale analysis of phenomena such as air, water and land pollution, invasive species and climate change –in addition to protecting unique geomorphological sites and providing multiple ecosystem services (Keiser et al., 2018), (Mahan et al., 2009), (Watson et al., 2014), (Arroyave et al., 2024).

The US National Park System is managed by the US National Park Service (a federal agency within the US Department of the Interior), and is a longstanding, well-ordered and clearly delimited set of protected areas, collectively encompassing 344,000 km^2 (an area nearly the terrestrial size of Germany). Given its size, diversity and socio-environmental complexity and value, the National Park system substantially depends upon managerial decisions and practices, which require the consideration of multiple factors incorporating environmental, behavioral, and financial uncertainty (Fancy and Bennetts), (Mahan et al., 2009), (Kaiser, 2000), (Kupper, 2009), (Parsons, 2004), (Sellars, 1997). The system management requires abundant knowledge to inform and guide decisions, nevertheless the available scientific knowledge might not address the most relevant or urgent knowledge demands (Soukup, 2007), (Mahan et al., 2009), (Britten, 1996), (Miller, 2008), (Newton, 2012).

In this work we address the issue of research (mis)alignment, defined as the degree to which the demand for scientific knowledge (e.g., park-oriented) is under- or over-supplied. We quantify the direction and degree of research alignment over time at both the parks and systems levels, by applying a standard unsupervised text-mining method to a comprehensive parks management-science corpus encompassing official park "needs statements" with scientific publication metadata (title, keyword, and abstracts). Hence, our analysis provides relevant insights into the management of national parks, and protected areas more generally, in two ways. First, by developing a framework for evaluating to what extent upstream knowledge producers (specifically, external researchers and National Park scientists) meet the demands of downstream knowledge consumers (specifically, National Park managers and scientists). And second, by evaluating how this alignment changed in response to a paradigm shift introduced around the 2000's in National Park science policy instituting parks as living laboratories.

The structure of this study is as follows. First, in Section 2 we motivate our study against the theoretical background of research alignment, and we expound on the historic relationship between science and parks, in particular the development of US science policy of National Parks (denoted hereafter by SPNP). We then describe our data and methodological approach for evaluating research alignment in Section 3. We summarize our findings by describing the areas in which alignments are found using a system-level analysis in Section 4.1, and then downscale our analysis at the park level in Sections 4.2 and 4.3. Finally, in Section 5, we discuss our results and the implications of our findings.

2. Background

In what follows, we introduce some elements required to understand how research alignment between science and society (or organizations) proceed. We begin by presenting some determinants for the supply of scientific knowledge —or *research priorities*— and then define the societal demand for knowledge —or *research needs*— and how they can be assessed. Finally, we introduce the science policy of National Parks (SPNP) and highlight the relevance of this policy to the preservation of natural and historical resources.

2.1. Relationship between research priorities and research needs

Research alignment, or the lack thereof (misalignment), is a concept that captures the relationship between the knowledge, information and societal outcomes provided by the scientific community, and the knowledge required to achieve specific societal or organizational goals (Sarewitz and Pielke, 2007). Note that research encompasses multiple activities aimed at producing knowledge and information, using a scientific basis. Alignment can be understood from an economic perspective as the efficient balance between supply (i.e., research priorities) and demand for knowledge (i.e., research needs). The concept "alignment" has gained relevance in the study of science and innovation policy and has been addressed through urgent issues such as medicine and public health, pharm-industries, agriculture, and climate change (e.g., (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Rafols and Yegros, 2017), (Sarewitz and Pielke, 2007), (Ostrom et al., 2010), (Petersen et al., 2016), (Ranson and Bennett, 2009), (Robinson-Garcia et al., 2019), (Wallace and Ràfols, 2018)). Although analysis of research alignment is relevant and informative (McNie, 2007), (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Tambe et al., 2023), (Kalafatis and Libarkin, 2019), there is scant literature developing these concepts further. For instance, there is little understanding of factors (i.e. drivers) affecting research alignment.

Understanding the dynamics in alignment requires comprehending how research priorities (i.e., supply) and research needs (i.e., demand) are set. First, many factors affect the dynamics of science[1] influencing what is researched and how frequently, and therefore, shaping the research priorities or the portfolio of available knowledge (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Rafols and Yegros, 2017), (Sarewitz and Pielke, 2007), (Ranson and Bennett, 2009), (Wallace and Ràfols, 2018), (Kalafatis and Libarkin, 2019), (Diamond and Adam, 2004), (Ely et al., 2014), (Fortunato et al., 2018), (Gläser and Laudel, 2016), (Maclean et al., 1998). On the other hand, describing what affects social and/or organizational research needs and what constitute them is challenging because research needs can be manifested in many ways and vary across physical, social, and organizational contexts (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Robinson-Garcia et al., 2019), (Ely et al., 2014), (Fleishman et al., 2011). Drawing on the taxonomy of needs developed by Bradshaw (1972), we focus on both *normative* and *expressed needs*. Normative needs are desirable standards that should be met, whereas expressed needs are those that an agent "feels" and takes action to satisfy. For the case of parks, normative research needs represent top-down (e.g., congressional mandates) knowledge requirements for adequate administration of resources, whereas expressed research needs are those actively pursue (bottom-up) by conducting research or promoting third parties to do so. Note that normative and expressed needs might intersect each other, and both needs might be

[1] These factors include science policies, extramural sources of funding, investment risk and expected outcomes, researchers' interests, peers' pressure, research networks, journals influence, researchers' expertise, among other factors.

partial and can differ depending upon the ability of agents (internal or external) to identify them (see (Devereux and Cook, 2000), (Bradshaw, 1972)).

Research priorities and research needs interact and might even coevolve according to common selection mechanisms. The development of new knowledge typically involves the production of new questions and future research. To some extent, the same could be expected for research needs; as needs are defined, they could illuminate the path for identifying the next layer of needs. Moreover, it could be expected that research needs trigger changes in research priorities, whereas scientific discovery could highlight knowledge gaps and societal unknowns that later become research needs (Fig. 1). As a result of such iterative processes, it might be expected that research priorities and research needs change and eventually become more aligned (Sarewitz and Pielke, 2007), (Fleishman et al., 2011).

The analogy of supply and demand for scientific knowledge is a straightforward framework to connect the dynamics of research priorities and needs. However, one underexplored dimension is how research is allocated along multiple knowledge domains in so far as research priorities and needs are not homogeneously distributed. We argue that the balance between the intensity in which a particular scientific knowledge domain is supplied and the intensity in which it is demanded would inform the degree of alignment of such domain. Specifically, a scientific knowledge domain could be perfectly aligned if supplies match the levels of demand; on the contrary, misaligned research could be produced by different degrees of oversupply or overdemand, representing a scenario of "missing opportunity" (Sarewitz and Pielke, 2007). Thereby, (mis)alignments can be understood by both the direction and magnitude of the supply-demand imbalance.

2.2. Science and science policy in US national Park system

The perceived benefits of parks as living laboratories are tied to the dynamics of science, nevertheless, knowledge production in parks has traditionally been neither explicit nor implicit. In contrast to much basic research, science in parks has been proposed as mission-oriented research (Parsons, 2004) important for managerial purposes (Sellars, 1997), (Brown et al., 2016), (Pringle and Collins, 2004), (Halvorson and Davis, 1996), (Jenkins et al., 2021). Hence, parks science is likely to be less influenced by confounding factors such as extra-mural funding prioritization (e.g., (Scown et al., 2019), (Ranson and Bennett, 2009), (Wallace and Ràfols, 2018), (Diamond and Adam, 2004), (Maclean et al., 1998)). As such, parks science is a well-delimited domain, corresponding to what Kitcher (2004) defines as a well-ordered science that is mostly driven by societal needs, laws (e.g., Clean Water Act, Endangered Species Act, and others listed in Supplementary Table 1), and research interests.

Although the current science commitment of parks seems natural, this has not been the case for substantial part of the system history. In fact, science was largely neglected throughout much of the history of parks (with some relevant but non-consolidated exceptions) and fully appreciated only recently in the late 1990s (Kupper, 2009), (Parsons, 2004), (Sellars, 1997), with the emergence of the policy change aimed at bringing scientific problems into focus, as opposed to management issues historically centered on visitation. Such a policy change represents a paradigm shift because it altered the role of science in parks management. A complete historical review of the science in parks is beyond the scope of this work, we nonetheless briefly describe the paradigm shift in what follows, and provide essential details and events associated with the history of science in parks in Appendix A.

The paradigm shift constituting the science policy of National Parks (SPNP) was established by way of a burst of interrelated policies and political initiatives emerging in the late 1990's and persisting thereafter (e.g., National Parks Omnibus Management Act; Natural Resources Challenge). Three interacting components shaped the SPNP: First, scientific and societal criticism that highlighted how the lack of scientific programs affected the socio-ecological integrity of parks (e.g., (Sellars, 1997), (Allen and Leopold, 1977), (Bishop, 1989), (Cain et al., 1972), (Council, 1992), (C. on R. H. of R. CRHR, 1997), (Franklin, 2001), (N. P. and NPCA, 1979), (NPS, 1980), (Robbins, 1963), (Rydell, 1998), (Pringle, 2000), (Shafer, 2012), (Wagner, 1999), (Dilsaver and Babalis, 2023)). Second, legal mandates to conduct science in order to protect natural and historical resources (see (Fancy and Bennetts), (Harmon, 1999), (Lowell and Kelly, 2016)), including the National Parks Omnibus Management Act (1998) which gave parks the legal authority to conduct scientific studies for management purposes. And third, the institutionalization of science in parks' management, embodied in several internal policies (Fancy and Bennetts) (see Appendix A).

The SPNP is framed from the quote "*Parks for Science, Science for Parks*", which rationale is to increase the scientific knowledge available for management by incentivizing universities and third parties to conduct research in parks (Soukup, 2007), (Rodhouse et al., 2016), (Mahan et al., 2009), (Parsons, 2004), (Newton, 2012), (Engquist, 2001), (Manning et al., 2016), (Soukup, 2004). This idea materialized in

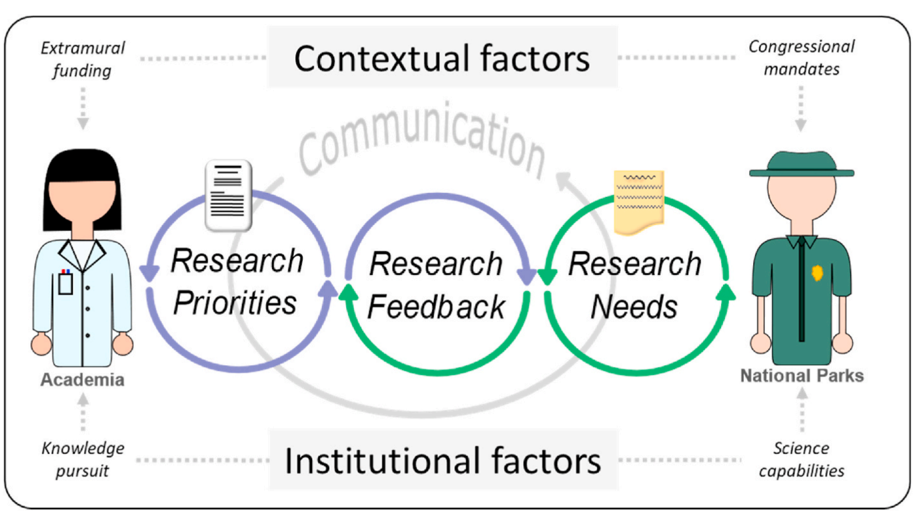

Fig. 1. Idealized schematic of the research feedback in the U.S. National Park System. Academia produces codified knowledge (research priorities) in research publications that are relevant for managing parks, whereas national parks identify their research needs and (re)codify them in multiple ways to inform scientists what knowledge is the most needed. New scientific knowledge also promotes the identification of new needs while needs induce the production of new knowledge ("research feedback"). Note that research priorities and research needs are affected by multiple contextual and institutional factors.

multiple fund streams to support researchers and to adequate the infrastructure necessary to conduct investigations and bring together scientists and parks managers (Kaiser, 2000), (Kupper, 2009), (Parsons, 2004), (Franklin, 2001) (for further details see Appendix A). The SPNP reflects the modern openness and willingness of parks to foster research. Interestingly, it is largely unknown whether science has met the knowledge required for the stewardship of parks and if the SPNP has indeed bridged the historical gap between the scientific community and parks (Sellars, 1997).

Accordingly, in this work we assess *to what extent scientific publications ("research priorities") and the knowledge demanded by parks ("research needs") are aligned?* And *what has been the impact of the SPNP on that alignment?* Consequently, this study contributes by identifying some implications of the current SPNP and brings insights to the discussion regarding science's organizational value.

3. Methods

The evaluation of knowledge alignment has taken place through multiple methodologies, for which the characterization of research priorities relies on cartographies of knowledge frequently based on scientific publications (e.g., (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Rafols and Yegros, 2017), (Wallace and Ràfols, 2018)). On the other hand, research demands have been addressed by using basic need indices (e.g. (Ciarli and Ràfols, 2019),), disease burden (e.g. (Rafols and Yegros, 2017),), interviews and stakeholder opinions (e.g. (Wallace and Ràfols, 2018), (Maclean et al., 1998)), and policy documents (e.g. (Cassi et al., 2017)), among other sources. Research needs vary by the nature of the investigation, their content, and how they are codified, all of which constitute an important challenge. To overcome the shortcoming that constitute matching heterogeneous sources (i.e., research priorities and needs), we quantify the magnitude and direction of research alignment by generating discrete and well-defined categories (i.e., knowledge cartography) that are used as units of analysis for estimating the balance between the supply and demand for knowledge. In what follows we describe the sources of information used for measuring knowledge alignment in the National Park System and then we introduce a conceptual model designed to operationalize the evaluation of research alignment. Importantly, this study focuses only on national parks within the National Park System, while recognizing that there are other protected areas in the system that might follow different research regimes.

3.1. Data

We use two data sources specifically related to research priorities and needs. We evaluate research priorities by analyzing scientific publications (i.e., articles, reviews, books, and conference papers) indexed in Web of Science (WoS). WoS is highly structured and one of the largest catalogues of scientific communication, frequently used for evaluating scientific outcomes (Leydesdorff et al., 2013). Although WoS does not include all scientific publications or non-peer reviewed publications, it is a reliable source of systematically indexed and annotated scientific knowledge.

The publications contained in WoS were retrieved using two queries[2] resulting in 17,326 research articles published between 1921 and 2020. Given the low abundance, we pooled all the publications produced in 1985 and before. Publications include information the affiliations of authors, title, year, keywords, and enhanced keywords (WoS standardized keywords). We limited our analyses to publications that met at least one of two criteria: one or more authors were affiliated to a National Park; or, one or more national parks are mentioned in the title, keywords or abstract. We applied these criteria by performing string matching across the publication's metadata. As a result, we identified 8088 publications developed in, or by parks belonging to the U.S. National Park System.

We leverage information regarding research needs from the Research Permits Reporting System (RPRS),[3] which is the official system for connecting researchers and the parks administration. In RPRS each park enumerates their research needs (termed 'research preferences') to inform researchers about the most urgent issues and the knowledge that parks consider require further investigation, without this meaning topical constrains for researchers. RPRS thereby provides a direct measurement (and therefore draws a realistic picture) of the park's research needs, which conceptually correspond to expressed research needs.

We inspected RPRS webpages for all national parks,[4] nonetheless some parks did not state their research needs or provide inaccessible sources. As such, we gathered the information for 36 out of 60 national parks (with three parks recently added, now totaling 63). Although it was impossible to access to the research needs to all the parks, we argue that our sample of 36 National Park units is representative as it covers a variety of parks through the country, encompassing most of the land cover, visitation, and budget allocation. Throughout this study we use the simplified acronyms that RPRS utilized to designate parks, listed in ST.2. We termed each element in the list of research needs as 'need statement'. When research needs were stated in prose, they were divided into individual need statements without including major changes in syntax or content. In total we count 1035 individual need statements, with noticeable variation across parks, varying from 2 statements at Everglades NP (EVER) to 155 for Sequoia and Kings Canyon NPs (SEKI). On average, there are 29 need statements per park.

3.2. Analytical approach

3.2.1. Model generation

An important challenge addressed in this study is the differences in both origin and intended purpose of the "research priorities" and "research needs" text sources. Hence, we first aim to establish a common set of topical intermediary categories based upon these two text sources (see Fig. 2). There are two general dimensional reduction methods for identifying topical categories: knowledge maps and topic modeling. Notably, both methodological approaches of knowledge cartography lead to similar outputs (Velden et al., 2017; Romero Goyeneche et al., 2022). Knowledge mapping approaches commonly leverage existing keywords ontologies or other article-level descriptors, useful as heuristics for defining categories of scientific knowledge (see e.g., (Fortunato et al., 2018), (Chen and Chen, 2003), (Ding, 2011), (Gates et al., 2019), (Grauwin and Jensen, 2011), (Romero et al., 2022), (Yang et al., 2021), (Zins, 2007)). In contrast, topic modeling is a more appropriate approach in the absence of ontology metadata.

Since there is no established ontology for parks concepts and entities, we apply Latent Dirichlet Allocation (LDA) topic modeling (see (Blei et al., 2003), (Griffiths and Steyvers, 2004), (Ponweiser, 2012)) to the text sources in union. LDA is a relatively general method, well-understood, and replicable natural-language machine learning algorithm useful for identifying underlaying topical structures (e.g., (Leydesdorff et al., 2013), (Griffiths and Steyvers, 2004), (Boyack, 2004), (Shiffrin and Börner, 2004), (Skupin, 2004)). LDA considers topics as probabilistic mixtures based on the co-occurrence of semantic structures between and within documents (i.e., publications and need statements, indistinctly). For each topic identified by LDA, one obtains a

[2] The queries used were "TS=(National Park*)" and "OO=(Natl pk)".

[3] The RPRS is available at: https://irma.nps.gov/RPRS/Parks/ResearchNeeds . The system allows one to search what research needs or preferences are declared by each unit in the NPS.

[4] We excluded other NPS denominations (e.g., monuments, battlefields) and restricted our analysis to national parks as the most emblematic units within the NPS.

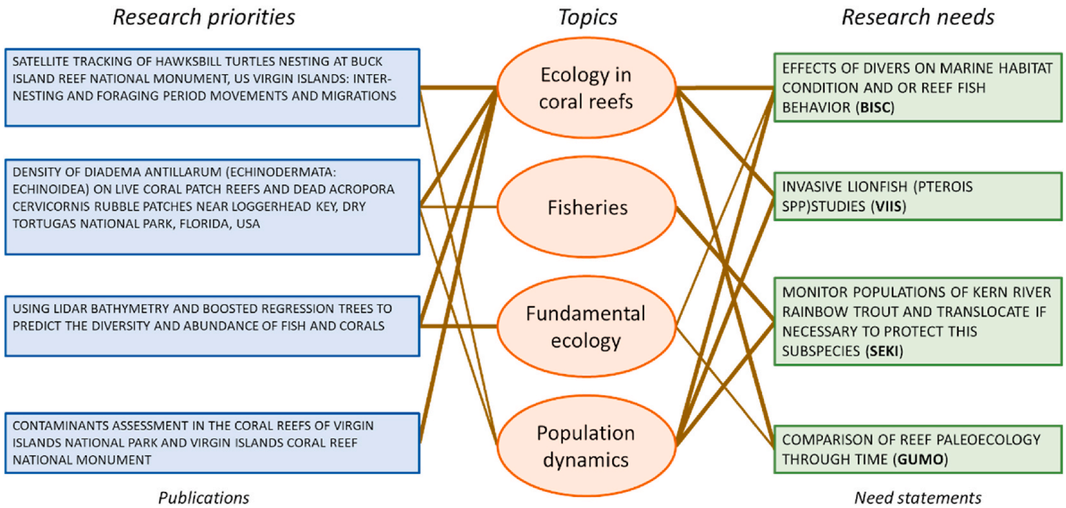

Fig. 2. Conceptual model for evaluating alignment between research priorities and research needs through topical categories. Research priorities correspond to publications, and research needs are official park-specific "need statements" (specific source NP indicated in bold). Research priorities and needs are associated with LDA topics with different strengths, as indicated by the variable thickness of the brown lines. The information used in the schematic corresponds to real data.

list of words that describe its composition and a list of probabilities (φ) that denotes the association of documents with each topic. We provide complete details of our LDA implementation in Appendix B. Importantly, to avoid the subjectivity associated with defining the correct number of topics -a frequent shortcoming in LDA implementations, and similar methods-, we followed the approach of Griffiths & Steyvers (Griffiths and Steyvers, 2004) and Ponweiser (2012), which consists of varying the number of topics incrementally until reaching convergence in the likelihood of coefficients.

Acknowledging the differences in written style, text format, abundance, and length between publications and need statements, we explored two factors that can affect our analysis, as further detailed in Appendices B and C. First, we systematically evaluate different combinations of publication metadata (i.e., title, abstract, keywords), identifying that the LDA model produced from text input comprised of full need statements and the title and keywords of publications are appropriate for capturing underlaying topics in the documents, in line with the scope of our study (Appendix B). Second, we perform a robustness analysis designed to assess the effect of semantic composition of documents by randomly interchanging words (i.e., substitute all "word 1" with "word 2", and vice versa) across all documents without affecting their statistical properties (i.e., length, word frequencies within and between documents). Our robustness analysis indicates that the topics found in the empirical documents cannot be captured by random configurations of documents (Appendix C) and therefore our results are not artifacts of the data structure. All LDA analyses were conducted in R (R Core Team, 2017) using the package topic models (Hornik and Grün, 2011).

Overall, we found that 40 topics generated by documents comprising need statements and publications metadata of similar length are adequate to capture the aggregated corpus (see Appendix B). Table 1 lists the identified topics and Supplementary Table 3 lists the 20 most relevant words defining each topic. We classified the topics themselves into two categories: normative and non-normative, as indicated by the asterisks in Table 1. We used relevant congressional mandates to differentiate normative (representing those following official US government standards) from non-normative topics. We provide a complete association between normative needs and corresponding legislature in

Table 1
List of 40 LDA topics used for assessing knowledge alignment in the US National Parks. Topics (T) were identified using the Latent Dirichlet Allocation (LDA) algorithm applied to scientific publication metadata and parks' need statements. We manually assigned a title to each T listed below based upon the 20 most prominent words associated with each topic. Topics denoted with ** are here associated with normative needs since they relate with congressional policies that mandate their study (see ST.4).

T-1	Ecology in coral reefs	T-21	Sustainability**
T-2	Ecology of amphibians	T-22	Biodiversity in the Rocky Mountains
T-3	Geology and paleontology**	T-23	Habitat use in deserts
T-4	Wetlands and restoration	T-24	Control of invasive ants
T-5	Marine ecology	T-25	Sierra studies
T-6	Fire ecology	T-26	Human impacts**
T-7	Volcanology	T-27	Fundamental ecology
T-8	Paleoclime and paleoecology	T-28	Visitation and recreation**
T-9	Bio and social studies in caves**	T-29	Ecosystems management**
T-10	Management and modelling**	T-30	Mammalogy
T-11	Air quality**	T-31	Species distribution**
T-12	Ecology in hot springs	T-32	Clime and climate change
T-13	Forest**	T-33	Ungulate studies
T-14	Ecological monitoring**	T-34	Population dynamics ecology
T-15	Floristics in Midwest	T-35	Forest and alpine ecosystems
T-16	Limnology	T-36	Pollution**
T-17	Fisheries and freshwaters	T-37	Nutrient cycles
T-18	Invasive plants	T-38	Environmental modelling
T-19	Invasive animals	T-39	Trophic interactions ecology
T-20	Bears' ecology	T-40	Landscape studies

Supplementary Table 4.

3.2.2. Alignment quantification

As illustrated in Fig. 2, using empirical examples taken from our data sample, topics identified by LDA are connected (with varying strength, defined as their association probability) to scientific publications and need statements that refer to similar issues and consequently relate to each other. With this approach, the relative (dis)parity in the composition of topics in terms of publications and need statements indicates the degree of (mis)alignment.

Several characteristics of our natural-language approach are worth mentioning: (i) publications and need statements are written in different styles, but nevertheless those connected via topics refer to similar issues; (ii) both scientific publications and need statements can be associated with multiple topics and the intensity or weight of such association might vary; (iii) while some topics in the example are well represented in both publications and needs statements (e.g., 'Ecology in coral reefs'), others are disproportionately weighted on one side (e.g., 'Population dynamics'). Indeed, this (dis)parity is the basis for the quantitative evaluation of research (mis)alignment that follows. For instance, 'Ecology in coral reefs' is well aligned because the supply/demand balance based upon connectivity from each domain is close to a 1:1 ratio, whereas 'Population dynamics' is misaligned, in this case representing an under-researched topic as the connections to need statements are stronger – and more numerous-than to publications.

Following this rationale, the degree of association between publications and need statements with each topic is based upon estimated probability of association (denoted as φ). It follows that the mean likelihood value of a topic calculated across all publications ($\overline{\varphi}_s$) represents how important that topic is in the supply domain (i.e., science). Similarly, the mean likelihood value calculated across all need statements ($\overline{\varphi}_d$) indicates the importance of a topic in the demand domain (i.e., parks). Therefore, we argue that the research alignment between the supply and the demand dimensions is quantified according to the relationship between $\overline{\varphi}_s$ and $\overline{\varphi}_d$. Note that in what follows, we calculate $\overline{\varphi}_s$ and $\overline{\varphi}_d$ at two levels of aggregation: for either the system level using the collection of parks units included in our sample, or for individual parks at different temporal scales.

4. Results

Topics found with our analysis illustrate a set of important knowledge domains for science and the National Park Service (Table 1). Although the identified topics might suggest a bias towards natural sciences, many capture multidisciplinary topic domains (e.g., T-21 'Sustainability'), and social and management sciences (e.g., T-28 'Visitation and recreation'). Because parks are socio-ecological systems, it is not surprising that the topics span the management, social, natural sciences, and convergent knowledge domains at their intersections (Arroyave et al., 2021), (Petersen et al., 2021).

Research alignment can be evaluated across two dimensions of park generality and specificity. First, regarding park generality, one can assume that scientific knowledge is beneficial to all national parks indistinctively. For instance, findings on water pollution may be informative to all parks in the system. Second, one can consider park-specific knowledge idiosyncrasies. Although characterizing the range of applicability of publications to each particular park is beyond the scope of this study, we nonetheless acknowledge that applicability of research findings is likely to vary between parks, just as research needs also vary across parks.

Consequently, in the following section, we first present the analysis based on a system-level investigation assuming that research findings are informative to all parks. We then downscale to park-specific analysis, where we leverage the implicit connection between the research publications associated with a given park (based upon string matching of title, abstract and keywords) and the needs statements of the same park.

4.1. System-level results using multiple national parks

Fig. 3a shows the relative prominence of each topic identified, quantifying research supply as the mean likelihood ($\overline{\varphi}_s$) calculated across all scientific publications; and quantifying research demand as the mean likelihood ($\overline{\varphi}_d$) calculated across all need statements for the 36 individual national parks included in our study. Perfect alignment corresponds to the 1:1 ratio between the two relative measures, represented as the diagonal in Fig. 3a. Deviations from the parity line indicate misalignment, quantified as the length of the bisect segment connecting a topic and the diagonal line, termed here as discrepancy (see for example the dashed line in Fig. 3a).

Topics can be differentiated into three groups according to their alignment. First, topics aligned, characterized by the proximity to the diagonal (i.e., small discrepancy) and denoted in dark colors, including domains such as "Landscape Studies" (T-40) or "Limnology" (T-16). Second, misaligned and over-researched topics showing large discrepancy values and localized above the diagonal, including domains such as "Ecological monitoring" (T-14) or "Mammalogy" (T-30). Finally, misaligned and under-researched topics localized below the diagonal including topics such as "Trophic interactions ecology" (T-39) or "Ecology in hot springs" (T-12).

Our results indicate that most of the topics are, to a great extent, aligned as their discrepancy is low (represented in dark color in Fig. 3a), whereas misaligned topics (represented in light colors in Fig. 3a) frequently are under-researched. The most aligned topics correspond to disciplinary domains (e.g., T-3 'Geology and paleontology'), whilst the most misaligned topics are complex and demanding domains (e.g., T8-'Paleoclime and paleoecology'). Additionally, most of the normative topics tend to have large discrepancy (misaligned) and typically are over-researched. Importantly, the results of the null model did not reproduce the observed pattern of topical alignment, indicating that our analysis is robust (see Appendix C).

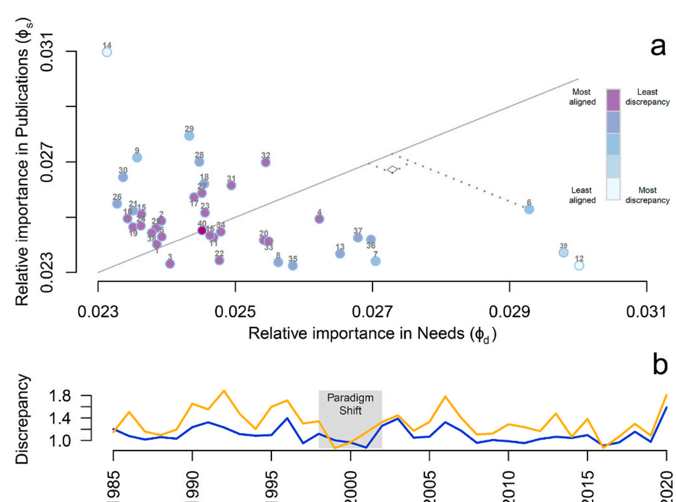

Fig. 3. Alignments between research priorities and research needs based upon data aggregated across US national parks. (a) Topics identified with the LDA model are plotted in terms of their relative importance in publications ($\overline{\varphi}_s$) and need statements ($\overline{\varphi}_d$), and colored according to their distance to the diagonal line – a quantity we termed discrepancy (see, the dashed line for Topic 6 that is orthogonal to the diagonal). (b) The change in the annual mean discrepancy across the 40 topics (blue) and for the normative topics (orange) normalized by the standard deviation calculated across topics of each type. The gray area represents the paradigm shift in parks management consisting of the emergence of the Science Policy of national parks. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

When analyzing how the research alignment has changed over time, we found that the absolute discrepancy (i.e., disregarding whether the data point is above or below the diagonal) has not systematically changed over time (Fig. 3b). Notably, topics associated with normative needs tend to be slightly less aligned (i.e., larger discrepancy) than the average calculated over the 40 topics (Fig. 3b). The temporal trend of the mean discrepancy shows that the topics were mostly aligned and very low values of discrepancy.

In general, our system-level results suggest that research priorities are aligned with research needs across many topics, and with some differences in alignment between expressed (all topics) and normative needs. We do not find clear evidence of systematic changes in the mean degree of alignment over time, particularly around the implementation time of the SPNP (Fig. 3b). Interestingly, our analysis identified many topics on cross-domain problems, which suggests that our results are not necessarily biased by the disciplinary disparities in publications. In particular, those topics related to social sciences are not under-researched as one might expect, but rather they appear to be intensively researched (e.g., T-21 “Sustainability” and T-28 “Visitation and recreation”).

4.2. Individual park-level results

To evaluate changes in knowledge alignment and its characteristics at the individual-park level we address discrepancies in two ways. First, we evaluate the distribution of discrepancies considering their sign to differentiate over-researched and over-demanded topics. Second, we assess the overall degree of (mis)alignment calculated as the total discrepancy (the sum of the absolute distances) as an indicator of the magnitude of (mis)alignment.

Fig. 4a shows the park-specific distributions of discrepancies, which tend to be centered around positive values representing over-supply, indicating that the topics are well-aligned or slightly over-researched on average. Yet there is considerable variation in the interquartile and total range of topic discrepancies, within and across parks. For instance, CARE (Capitol Reef NP) is a park in which some topics are extremely over-demanded, whereas VOYA (Voyageurs NP) represents a case in which topics are evenly distributed above and below the diagonal, as shown by the mean located near zero, although the distribution is rather wide. SEKI (Sequoia and Kings Canyon NPs) had the most need statements, and its distribution is quite narrow and right skewed, indicating that most of the topics were fairly well aligned or slightly over-researched.

The total (absolute) discrepancy captures the overall degree of (mis) alignment. We evaluate how this metric varies over time for each park (Fig. 4b; see Appendix D for all the parks), identifying some differences in the trend that each park follows. While some parks are rather stable (e.g., Yellowstone NP -YELL-, Great Smoky Mountain NP -GRSM-), others feature a significant increase (e.g., Katmai NP -KATM-) or decrease (e.g., Arches NP -ARCH-) over time. Consistent with the results

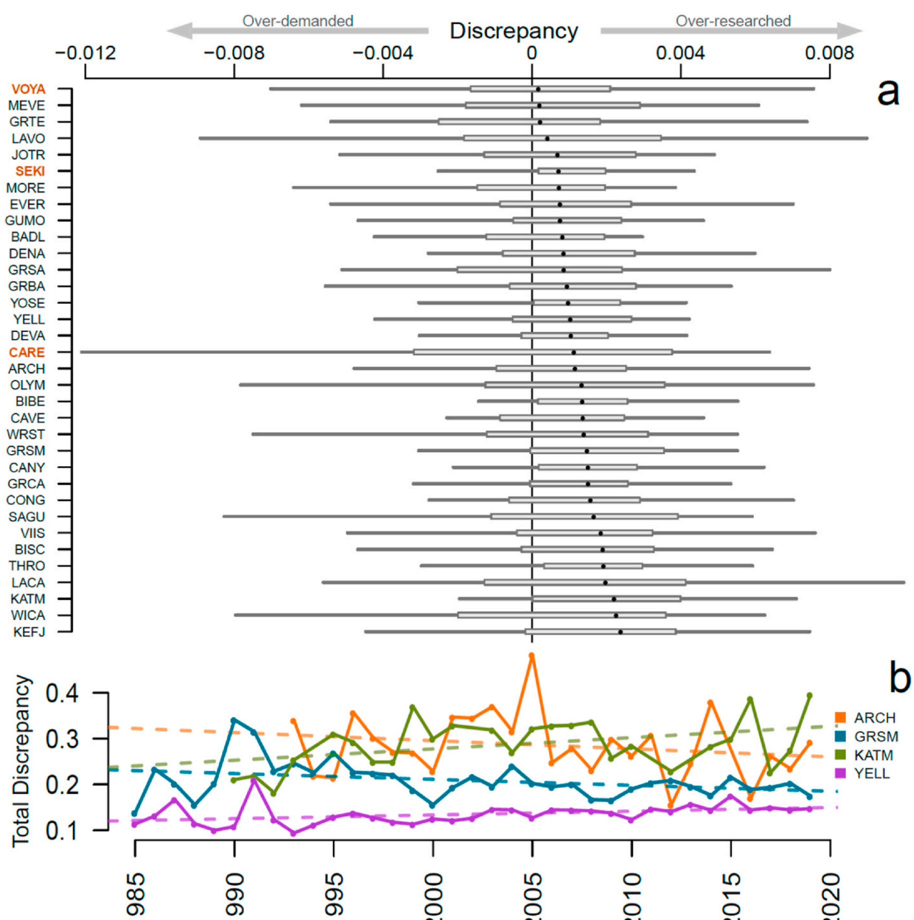

Fig. 4. Spatial and temporal variation in the degree of alignment between research priorities and research needs across US national parks. (a) Spatial alignment evaluated as the distribution of topic discrepancies based upon needs statements and publications directly associated with each park. Parks are labeled according to their official acronyms; those mentioned in the text are colored brown. Distribution of discrepancies are represented as boxplots for which dots indicate the median discrepancy; the median value is used to sort the parks. (b) The temporal variation of alignment is measured as the total discrepancy and shown for 4 parks. For illustrative purposes, the linear trend (dashed line) for each park is included, estimated by ordinal least squares (OLS). Temporal variation for all the parks can be found in Appendix C. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

found at the system level (Fig. 3b), we did not identify a dominant increasing or decreasing park-level trend (see Appendix D).

Notably, we explored the relationship between parks' characteristics (e.g. size, budget, visitation) and the overall degree of alignment, but no significant relationships were found (See Appendix E). Furthermore, we did not observe any significant Pearson's correlation between the mean, median or total discrepancy with the number of publications found in each park ($R^2 = 0.003$; $R^2 = -0.305$; $R^2 = -0.230$, respectively) nor the number of need statements declared ($R^2 = -0.327$; $R^2 = -0.153$; $R^2 = -0.217$). Hence, it is unlikely that these park level results arise from variation in the sample size of publications or need statements.

4.3. Policy evaluation and parks-science alignment

Finally, we apply ANOVA to assess the relationship between research alignment and the documented paradigm shift (i.e., SPNP) around the year 2000. To be specific, we test for shifts in characteristic discrepancies, calculated by grouping park-topic-year discrepancy values into 4 non-overlapping subsets separating normative and non-normative topics measured before and after 2000. To account for park-specific variation (as indicated by Fig. 5), we normalized discrepancy values such that d_i are defined as the annual discrepancies for each topic (k) and park (j) divided by the typical standard deviation of each topic (σ_i).

We first tested for a statistically significant shift in the mean d_i value associated with the introduction of the SPNP by comparing values calculated before versus after 2000. Results indicate no relation between the introduction of the SPNP and the overall topical alignment (*t value* = 0.545; p-value = 0.586). When comparing the mean d_i value conditional on the topic being normative versus non-normative, we found non-normative topics to be statistically more aligned than normative ones (*t value* = 8.876; p-value< 0.001).

Based upon these two results, we calculated the Difference in Difference (DiD) between normative and non-normative topics, calculated before and after 2000. Such a DiD measures the shift in mean non-normative discrepancy, relative to the normative baseline, associated with the introduction of SPNP. Fig. 5 summarizes the results of the ANOVA, which indicate that SPNP exacerbated the difference between normative and non-normative topics (*t value* = −2.139; p-value = 0.033). Hence, while SPNP did not appear to directly affect topical alignment, its introduction does correlate with a divergence of alignment between normative and non-normative topics. These results are consistent with the implications of mandated researched in focus areas, which served to over-stimulate normative research and, consequently, leading to a higher degree of misalignment.

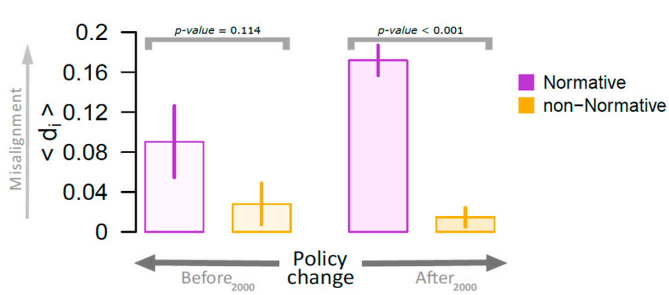

Fig. 5. Evaluation of how shifts in science policy of the US national parks (SPNP) correlate with shifts in park-level misalignment, assessed by way of mean topical discrepancies. Each bar shows the mean topical discrepancy $\langle d_i \rangle$ (calculated for park-level observations that are appropriately standardized to account for characteristic park-level variation levels) and the corresponding standard error of the sample mean (indicated by the vertical line). Note that divergence from 0 corresponds to greater misalignment. Park-year-topic discrepancy values are separated into four groups, corresponding to normative and non-normative topics, and for years before and after 2000 corresponding to the approximate peak of SPNP.

5. Discussion

Despite the clear need for science-based research to inform organizational decision-making, what is researched does not always correspond to the most relevant or urgent research needs (McNie, 2007), (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Scown et al., 2019), (Tambe et al., 2023), (Sarewitz and Pielke, 2007), (Maclean et al., 1998). Understanding how and when such misalignment arises is critical to inform policy. To this end, we developed a generalizable framework that can be extended to multiple systems and that is designed to quantitatively evaluate the alignment between scientific knowledge production and the demand for knowledge. Such a quantitative evaluation relies on a robust methodology based on pairing research priorities and needs through a comprehensive set of topic categories. As such, this framework enables (1) identifying knowledge domains that are over-researched or under-researched; (2) evaluating spatiotemporal trends in research alignment; and (3) measuring the impact of policy change or other relevant events on research alignment.

The idea of parks as a mission-oriented and well-ordered research system (Parsons, 2004), (Kitcher, 2004) supposes that science in parks should be aligned with managerial needs. Whilst our analysis of research alignment in U.S. national parks indicate a mostly positive scenario where most of the research is aligned, and the pool of under-researched topics corresponds to idiosyncratic, complex and generally demanding problems that one might expect to be misaligned (e.g., "Fire ecology" T-6); our results suggest that longstanding efforts promoting favorable conditions for parks science (Kaiser, 2000), (Parsons, 2004), (Halvorson and Davis, 1996), (Dilsaver and Babalis, 2023), (Harmon, 1999), (Manning et al., 2016), (Soukup, 2004) have not fostered improved research alignment, at least for the collection of national parks here evaluated. In particular, we find that the science policy of National Parks (SPNP) may have exacerbated pre-existing levels of misalignment – i.e., increasing the disparity between normative and non-normative topics. Our result may be the natural outcome of governmental funding streams oriented towards urgent issues and mandates defined around normative needs; however, this does not imply that the original policy is meeting current needs associated with under-researched topics corresponding to pressing challenges (e.g., climate change). Importantly, considering scant resources characterizing National Park management, it is likely that over-researched topics may flourish at the expense of other prioritized topics. We therefore argue that co-production and co-prioritization of research approaches are necessary to address the management needs of individual protected areas and park systems at large.

Robust research programs that foster research alignment promise to contribute to organizational challenges by providing fundamental knowledge necessary for managing systemic complexity (Helbing, 2013), (McNie, 2007), (Tambe et al., 2023). Yet, what makes a system better aligned is not completely clear. Moreover, a perfectly aligned research system is not necessary a desirable state, particularly when needs become outdated, as is the case when the source problems that originate needs evolve more rapidly than the ability of problem-solvers to identify, coordinate around, and address such problems. Whilst the paradigm shift represented by the SPNP that brought together scientists and organizational actors in the co-production of knowledge could favor alignment, our results indicate that such science policy may overemphasize certain types of research topics, giving rise to systemic inefficiencies in research allocation (misalignment).

In addition to inefficient mechanisms for prioritizing research agendas, research alignment can be affected by systemic conditions such as internal institutional processes, the restrictive nature of congressional mandates, and lags in science policy development (Fig. 1). As such, the centralized and multilevel governance structure of the National Park System, lower levels of parks scientist autonomy, acute preferences of parks managers (i.e., superintendents), law compliance (e.g., National Environmental Policy Act -NEPA-mandates aimed at reducing intervention in ecosystems), and delays at the interface between needs identification, policy development and practice, can together manifest in activity bottlenecks, thereby hindering proactive action upon research needs. Whereas systemic conditions can foster institutionalization of certain agendas, the rigidity and vertical organization of the system may limit the scaling-up of both local and system-wide efforts. Funding preferences might steer research towards knowledge domains currently over-researched or those considered by upper-lever administrators as managerial priorities. Systemic conditions might obstruct the identification and implementation of science-parks-policy configurations that enable rapid knowledge production and communication. Investing in plural and transdisciplinary governance model, such as traditionally posited for university-industry-government relations (Etzkowitz and Leydesdorff, 2000), (Leydesdorff, 2000), (Leydesdorff and Etzkowitz, 1996), could better facilitate the generation of innovative solutions by leveraging the strategic supply-demand-facilitator configuration (Petersen et al., 2016), (Romero et al., 2022), (Leydesdorff, 2000), (Leydesdorff and Etzkowitz, 1996), (Jagannathan et al., 2023), (Penna et al., 2023).

Complementary support for more strategic and dynamic science-parks-policy interactions is provided in the research alignment literature, which posits highly aligned sciences as an ideal state, and research misalignments as undesirable outcomes (Cassi et al., 2017), (Ciarli and Ràfols, 2019), (Devereux and Cook, 2000), (Tambe et al., 2023), (Sarewitz and Pielke, 2007), (Ranson and Bennett, 2009), (Maclean et al., 1998). Against this, our results raise three important points. First, the complex nature of some research areas might imply large misalignment given the difficulty of producing and leveraging relevant scientific knowledge and does not necessarily imply neglect on the part of the research community. Second, not all misalignments are equally undesirable. Indeed, in some circumstances over-researched topics might be preferable if urgency to make headway on such issues is required. Third, we acknowledge that normative enforcement of science can facilitate the allocation of the resources necessary to conduct research in urgent issues, although the narrow perspective of top-down science governance strategies might exacerbate misalignments. As such, there is a need for improved adaptive coordination between researchers, knowledge users and policymakers towards transdisciplinary settings oriented to define and prioritize better align knowledge production around urgent problem domains. Such democratization of the prioritization of knowledge might help rectifying the perceived misalignment in knowledge supply-demand (McNie, 2007), (Gläser and Laudel, 2016), (Owen et al., 2012), support the inclusion of multiple voices in the negotiation, design, and development of common research agendas (Arroyave et al., 2021), (Jagannathan et al., 2023), (Penna et al., 2023), recognize the adaptive nature of complex systems as well as their multiscale variability (Petersen et al., 2021), (Scown et al., 2019), (Arroyave et al., 2024), (Etzkowitz and Leydesdorff, 2000), engage researchers in delivering accessible knowledge and ensure a wide range of stakeholders (e.g., federal agencies, parks administrators and scientists) with the capabilities to absorb and use the knowledge (McNie, 2007), (Petersen et al., 2021), (Romero et al., 2022), (Yang et al., 2021).

We acknowledge some limitations in our study and potential for improvement. First, the official parks need statements used are aggregated over time, which negatively affected our ability to assess the coevolution of science–parks alignment. Further to this, it is important to note that some parks do not report their research needs, while other codify their research needs in park-specific sources like internal briefs or research-oriented policies, affecting the ability of researchers to identify parks research needs, like in our case. Hence, we recommend that systems reporting official research needs to be updated in order to include time-stamps to facilitate multi-scale analysis and decision support. Second, our study is limited to National Park denomination, which represents a small, albeit representative, fraction of the protected areas on the U.S. National Park Service. Identifying differences in research practices and alignment between protected area denominations requires further investigation. Third, our assessment of park needs was based upon a set of systematic statements associated with each park, which nevertheless are of unclear source generation, incomplete in some cases, and absent for some parks. Interviews and other participative methods could improve completeness, and better identify idiosyncratic needs that could be decomposed and weighted according to stakeholders' perception and preferences (Arroyave et al., 2021), (Cassi et al., 2017), (Devereux and Cook, 2000), (Arroyave et al., 2024), (Ostrom et al., 2010), (Ranson and Bennett, 2009), (Wallace and Ràfols, 2018), (Diamond and Adam, 2004), (Ely et al., 2014). Fourth, further work is needed to evaluate the research alignment in parks using other sources of information used by parks in their decision-making process, as some of the research developed in-house is not published (or designed to be published) in academic journals. Whilst non-peer reviewed publications and other academic publications (e.g. Master and PhD dissertations) are beyond the scope of this study, it is worth mentioning that such publications are not expected to be fundamentally different to scientific publications in terms of their disciplinary structure as a portion of them might overlap with scientific publications. Therefore, it could be expected that research alignment of 'gray-literature' follows a similar pattern of what has been shown in this study. Fourth, the mechanisms that enable the alignment between the supply and the demand for knowledge are still poorly explored. Although we assess the effect of policy change, it is necessary further research evaluating how research capabilities, funding, and natural, social, and organizational arrangements, among other factors, affect research alignment. Finally, we were faced with the common tradeoff of comprehensive generality versus contextual specificity. Our model lacks appropriate depth to effectively evaluate whether the knowledge produced can indeed be operationalized by the beneficiaries —parks in our case. In other words, our model can assess knowledge alignment but not its actionability, which requires further investigation.

In conclusion, managing national parks, as well as other protected areas governed according to visitation and conservation mandates, is a complex endeavor owing to the canonical challenges of management under uncertainty and finite resources, but also exacerbated by the inherent complexity of intertwined social and ecological systems (Amaral and Uzzi, 2007), (Arroyave et al., 2021), (Arroyave et al., 2024), (Halvorson and Davis, 1996), (Jenkins et al., 2021), (Romero et al., 2022), (Justin Nowakowski et al., 2023). More knowledge certainly is beneficial; notwithstanding, protected areas in general, and National Park in particular, require capabilities for absorbing such knowledge. As historical criticisms have claimed, the autonomous scientific capabilities of parks are always a subject of improvement (Soukup, 2007), (Fancy and Bennetts), (Sellars, 1997), (Harmon, 1999). Part of this enhancement is the development of adaptive policies that better steer resources allocation and adequate systems for informing and engaging researchers around current (and updated) parks' needs. Such improvements would not only boost research alignment, but also potentially improve the protection and management of the already-scarce protected lands and their value as living laboratories. In addition, more strategic science–parks-policy interactions that recognizes the complexity of parks and the interconnected nature of impacts and knowledge development (Helbing, 2013), (McNie, 2007), (Petersen et al., 2016), (Jagannathan et al., 2023) might strengthen the accomplishment of the parks mandate of 'keeping resources unimpaired, for the public, forever'.

CRediT authorship contribution statement

Felber J. Arroyave: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Jeffrey Jenkins:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Steve Shackelton:** Writing – review & editing, Conceptualization. **Breeanne Jackson:** Writing – review & editing, Writing – original draft. **Alexander M. Petersen:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.120699.

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